

There's (still) plenty of room at the bottom

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ABSTRACT

For more than a century, scientists and engineers have focused their efforts on improvements to large-scale heat engines. This paper argues that global climate change and public health considerations suggest that significant effort should be directed to the improvement of biomass-burning cook stoves used by billions in the developing world.

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1. Apologies to R. P. Feynman

In 1959, the Nobel Prize winning physicist, Richard P. Feynman, presented a lecture at a meeting of the American Physical Society (held at the California Institute of Technology, Feynman's home institution) with (nearly) the same title as we have used for this paper. Feynman suggested the possibility of “construction” on the atomic scale: “In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.” With the rise of nano-technology, that talk is now referenced frequently [1].

The intent of this paper is to suggest a similar opportunity in small-scale energy production. Interest, research, and engineering effort in the fields related to energy conversion, and particularly the conversion of heat to electricity, has focused on large-scale power plants since Edison switched on the Holborn Viaduct plant in London and built the Pearl Street Station generating plant in Manhattan, both in 1882. To this day, 130 years after Edison's successes, most research and development is still directed toward systems that produce large amounts of power – from 50 kW (e.g., automobile engines) to coal and nuclear plants with power generation capabilities in excess of 1 GW.

Two aspects of technology have changed over the past two decades that motivate a re-examination of the power generation infrastructure, especially in developing countries. First, the recent

rise of useful low-power electronics and high-efficiency lighting (e.g., fluorescent tubes and LEDs) means that significant benefits can be realized with substantially less power. Secondly, the same time period has seen a substantial increase in concern about the waste products that accumulate in the atmosphere causing potentially cataclysmic global consequences [2]. These shifts lead to the idea that there now may be some important applications of very small-scale ($<100W_{el}$) distributed electrical power generation to serve the 1.5 billion inhabitants of this planet currently without access to an electrical distribution grid [3]. Of course, that quarter of our world's population, which is without electricity, is concentrated in developing countries. For example, in Africa, the countries of Burundi, Chad, Central African Republic, Liberia, Rwanda, and Sierra Leone have between 95% and 97% of their population without access to electrical service.

2. The energy impoverished, cook stoves, health, and climate change

Even a small amount of electricity can be transformative. It can provide power for high-efficiency electrical lighting that let children study at night or provide parents with the opportunity to produce items at home that can be sold to generate additional income. Small amounts of electricity can provide connection to family, markets, and opportunity via radio, cellular telephones, and other small electrical appliances.

As evident in Fig. 1, the same 1.5 billion people who lack electrical services are also using biomass burned in “three-stone fires” to cook their meals. These open fires are responsible for 75% of the

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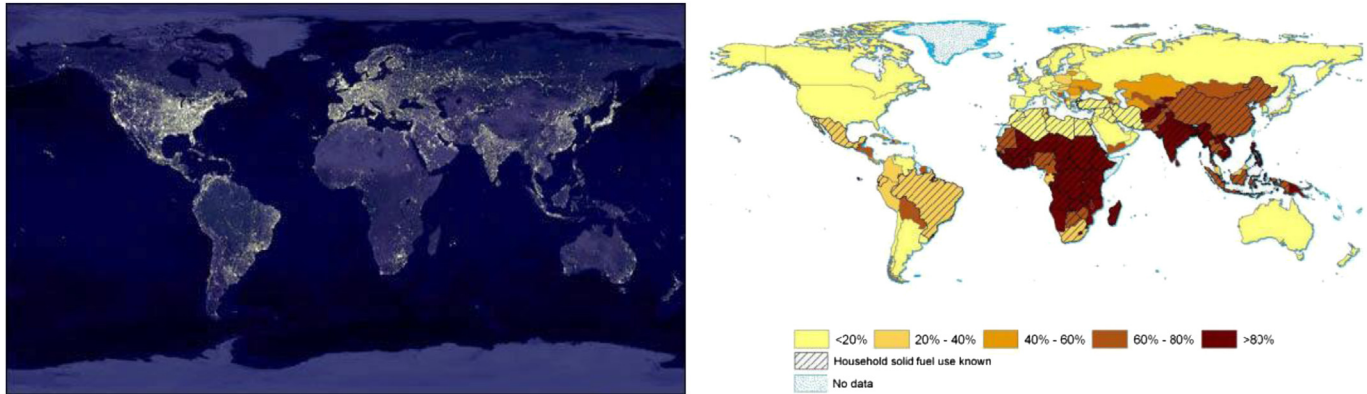


Fig. 1. (Left) Composite photograph of the Earth at night [National Aeronautic and Space Administration]. (Right) Distribution of national household solid fuel use in 2000 [World Health Organization].

black carbon which is the cause of the Asian Brown Cloud [4,5] and constitute a larger contribution to global warming than the CO_2 produced in those developing countries [6].

Reduction of black carbon (BC) and other products of incomplete combustion (PIC) is an attractive approach to mitigation of the effects of global warming in the short-term because BC has an atmospheric lifetime that is shorter than two weeks, whereas the atmospheric lifetime of CO_2 is centuries and has a long-time tail of approximately 30,000 years [7]. It has been estimated that removal of BC could delay the predicted consequences of global warming by a decade or two, thereby providing time to craft politically palatable solutions to limit CO_2 emission [Wallack and Ramanathan, 2009]. Additionally, improved cook stoves are an attractive policy alternative because they also improve the health of women and children and reduce deforestation [8].

A biomass-burning cook stove that can convert a small amount of the thermal energy produced by the stove (typically 4 to 8 $\text{kW}_{\text{Thermal}}$) into electricity makes the improved stove a stronger value proposition in many areas. Finally, a small amount of that electricity can be used by the stove itself to power a fan ($\leq 2W_{\text{el}}$). It has been shown many times that forced convection is the best way to reduce the products of incomplete combustion emitted by traditional stoves [9]. Also, the relatively small amount of heat removed to produce electricity is compensated by the increase in combustion efficiency.

3. Small-scale co-generation technological benchmarks

Difficult questions surround the options for using electrical power co-generation technologies at small-scales. To date, thermoelectric, steam, Stirling cycle, and thermoacoustic methods have been demonstrated for co-generation of electricity as a by-product of cooking [10]. These options represent different trade-offs between simplicity and efficiency. The simplicity of thermoelectric modules that convert a temperature difference directly to an electrical current provides a benchmark for other technologies that may be more efficient but also more complicated. For example, free-piston Stirling engines have very high efficiencies but are too expensive for use with individual or institutional biomass-burning cook stoves. The challenge is to find some parameter space that optimizes efficiency and minimizes the cost of both manufacture and maintenance.

3.1. Thermoelectric (TE) modules

The thermoelectric (TE) approach is the closest to commercialization and provides a useful benchmark, since it has been

developed by sophisticated manufacturers (e.g., Philips and Bio-Lite[®]) and is currently being field-tested. The reason for the fact that thermoelectrics have shown the most progress in the cook stove co-generation application is the simplicity of their operation – apply a temperature gradient across a commercially-available thermoelectric module and direct electrical current is generated. This simplicity has made thermoelectric generation attractive for spacecraft power generation using heat produced by the decay of radioactive materials. These TE generators are known as Radioisotope Thermoelectric Generators (RTGs) [11] and are particularly attractive for spacecraft that are launched in directions that takes them farther from our Sun, where photovoltaic generators (solar panels) have far lower power density.

Serious efforts to exploit thermoelectricity [12], also known as the Seebeck effect [13], for cook stove co-generation was documented in a Ph.D. thesis by Dan Mastbergen [14]. He included models and analysis for the combined sub-system (e.g., TE module, heat exchangers, fan, battery, and power management electronics). Mastbergen integrated a thermoelectric co-generator within an Ecoforno[™] biomass-burning cook stove,¹ after laboratory testing and modeling, that led to component optimizations. Lab tests were followed by field tests in Nicaragua and in Nepal.

Mastbergen's TE co-generators used a fan to provide enhanced convective heat transfer from the low-temperature (exhaust) heat sink, but did not attempt to use the forced air flow to enhance combustion efficiency and reduce emissions of PICs. Two commercial prototype stoves have been developed to utilize the TE co-generator's output to power a fan intended to improve combustion. The Philips "Woodstove" [15] and the BioLite[®] Home Stove² are shown in Fig. 2. Both pass air over the TE module's exhaust heat exchanger before injecting it into the stove's combustion chamber and both use bismuth telluride (Bi_2Te_3) modules.

The simplicity of the TE approach has its costs, both practically and thermodynamically. TE modules must place their active semiconductor elements electrically in series to develop useful voltage levels but must place them thermally in parallel to subject each element to the same full temperature difference. The elements are joined by a soldered connection that could cause the entire module to fail if only one of the electrical joints fail. For Bi_2Te_3 modules, failure will occur when temperatures exceed about 300 °C. The module's output increase with increasing temperature

¹ <http://www.english.ecofogao.com.br/modelos.html>.

² <http://biolitestove.com/homestove/overview>.

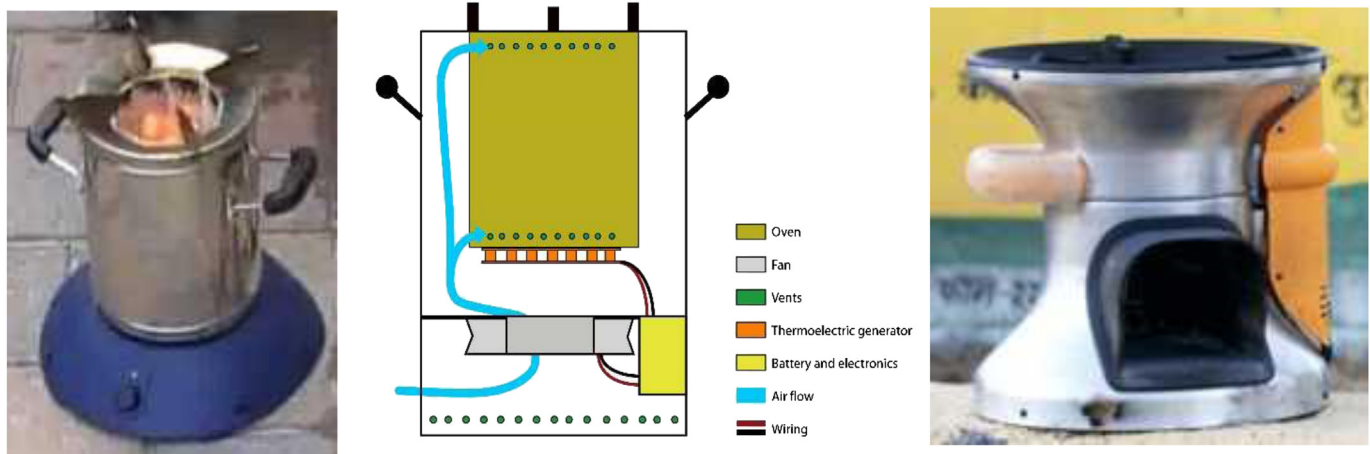


Fig. 2. (Left) Philips Woodstove uses a battery and TE module to power the fan shown schematically at the center [courtesy of Philips]. (Right) BioLite® cook stove with the fan and thermoelectric module contained in the orange-colored structure at the right side of the photo. In addition to providing power for the fan, the BioLite® unit provides a USB connector to power external electronics like cell 'phones or high-efficiency lighting'. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difference, as does the rate of output degradation and the rate of failure. This may also limit the scalability of this approach.

The temperatures available within biomass cook stoves are typically as high as 700 °C. If we assume an exhaust temperature of $T_{\text{cold}} = 80$ °C, then the maximum thermodynamic (Carnot) efficiency, $\eta_{\text{max}} = (T_{\text{hot}} - T_{\text{cold}})/T_{\text{hot}}$, over the stove's full temperature span is 64%. If the maximum temperature of TE module is restricted to $T_{\text{hot}} = 250$ °C, as typically recommended by the manufacturer (e.g., Tellurex³), then the maximum efficiency is reduced to 33%. Of course, the TE module's efficiency is a small fraction of η_{max} , typically a tenth; and that net efficiency, $\eta_{\text{net}} = \Pi_{\text{el}}/Q_{\text{hot}} \leq 4\%$, is a fairly strong function of both the temperature span and the electrical impedance of the load.

There is very little prospect that the efficiencies of TE modules will increase. This is a consequence of the fact that the TE module is constrained by two conflicting optimization requirements: The most significant losses in a TE module are due to Joule heating caused by the electrical current flow through the internal electrical resistance of the module itself and by the conduction of heat through the module in response to the temperature difference required to produce the Seebeck effect. Since it is electrons within the material that are responsible for both the module's electrical conductivity σ and its thermal conductivity κ , reduction in the module's electrical resistance results in an increase in its thermal conductance. In metals, this ratio is determined by fundamental constants, $\kappa/\sigma = (\pi^2/3)(k_B/e)^2T$, where k_B is Boltzmann's constant, e is the charge on one electron, and T is the absolute (Kelvin) temperature. This result has been verified for a large number of metals and is known as the Wiedemann–Franz law [16].

3.2. Steam, Stirling, and thermoacoustics

Other heat engine cycles can exploit the stove's full temperature span, hence enjoying higher Carnot efficiency, η_{max} . Other cycles also exhibit efficiencies that have higher ratios of $\eta_{\text{net}}/\eta_{\text{max}}$ than TE, but at the cost of significantly more complicated execution. Unlike the TE approach, these more efficient heat engines also require a dedicated transduction mechanism (see, for example Liu, 2005

[17]) that converts the mechanical power produced by the engine to electrical power for the fan and other uses. Three other heat engine and transduction strategies, involving a reciprocating piston-drive steam engine, a Stirling engine, and both standing-wave and traveling-wave thermoacoustics [18] were reported at the ASEAN-U.S. Next Generation Cook Stove Workshop [9].

The BMG LUX[®] Bio Micro Generator⁴ uses a small piston-driven steam engine (similar to a very small locomotive) and a gear-coupled permanent magnet alternator to generate electricity that charges a battery. The integrated stove and electrical system includes sophisticated switch-mode electronic power controls for battery charging and load management and can produce a peak power output in excess of 100W_{el}. In typical use for 4 h per day, the system delivers 435 W-hr/day, providing lighting and powering several small appliances, typically including a television. The stove-generator combination mass is 120 kg (≈ 265 lbs) and the overall electrical system efficiency is only about 1%.

At present, about four-hundred BMGLUX[™] units have been manufactured in a dedicated facility and installed in homes in the Amazon jungle at the cost of \$3200/each, including transportation, set-up, and user training. Financial support was provided under a program created by the Brazilian government to provide rural electrification in villages that are not going to be serviced by a centralized electrical grid.

Both kinematic and free-piston Stirling engines have been developed that can burn biomass for rural use. Sunpower, Inc. (Athens, OH) has produced compact (0.6 kg) free-piston Stirling engines that operate over cook stove temperature spans ($T_{\text{hot}} = 650$ °C, $T_{\text{cold}} = 80$ °C) and include an electrodynamic alternator that produces 43W_{el} operating at 105 Hz, with $\eta_{\text{net}} = \Pi_{\text{el}}/Q_{\text{hot}} \leq 32\%$, when pressurized to 2.6 MPa with helium gas [19]. At that operating point, the thermo-mechanical efficiency (excluding the electrodynamic alternator) is an impressive 57% of the Carnot limit, $\eta_{\text{max}} = (T_{\text{hot}} - T_{\text{cold}})/T_{\text{hot}}$.

A biomass-burning kinematic Stirling engine intended for electrical power generation (optimized for water purification by pre-heating water prior to treatment in a vapor compression distillation unit) has also been demonstrated [20]. In this case, the Stirling engine was intended for use in developing countries but is a

³ In addition to thermoelectric modules, Tellurex produces a "World Pot" that is "a common teakettle with an implanted high performance Tellurex thermoelectric module and a USB port".

⁴ <http://www.bmgflux.com.br/en/bmgflux/bmgflux.html>.

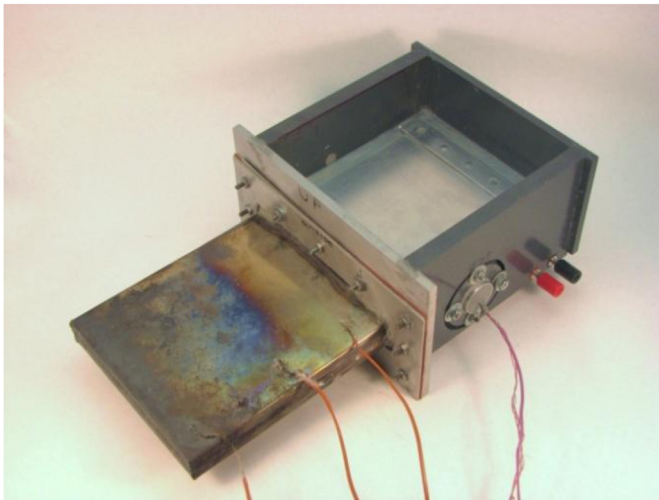


Fig. 3. Two prototype proof-of-concept thermoacoustic electrical generators designed to extract a small amount of heat from biomass-burning cook stove to generate electricity in villages that do not have access to electricity. (Left) Development of this prototype was supported by the P. S. Veneklasen Research Foundation (www.veneklasenresearchfoundation.org) and used a ceramic stack in a standing-wave thermoacoustic engine to drive a commercial 4" electrodynamic speaker using air at atmospheric pressure as the working fluid and electromagnetic radiation to transport heat from the stove to the hot-end of the stack [22]. (Right) A more sophisticated traveling-wave thermoacoustic engine laboratory prototype constructed by Aster Thermoakoestische Systemen (www.aster-thermoacoustics.com) in the Netherlands uses four regenerators and eight heat exchangers to convert the stove's heat to sound and then to electricity. The version shown was supported by the FACT Foundation (www.fact-foundation.com) and is designed to produce 50 W of electrical power [23].

very sophisticated machine that operates in high pressure gas with a prohibitively high acquisition cost.

Recently, several research groups have tried to find a compromise between cost and efficiency by attempting to create Stirling-like heat engines that substitute acoustic oscillations between gas inertia and compliance to eliminate the costly components (*e.g.*, gas bearings, pistons, linkages) and to reduce the need to maintain cleanliness and tight manufacturing tolerances required for Stirling engines by using thermoacoustical design principles [21]. Two attempts that are currently under development in the US using a standing-wave thermoacoustic engine [22] and the Netherlands using a traveling-wave thermoacoustic engine [23] shown in Fig. 3. Another traveling-wave thermoacoustic-Stirling configuration has been under development in the UK for several years [24]. All three thermoacoustic engines use electrodynamic transducers, similar to ordinary loudspeakers, to convert the acoustical power to electrical power.

4. Related energy policy issues

Thus far, the focus of this analysis has been on the technical and engineering trade-offs, but it is equally important to realize that potential solutions for alleviation of rural energy poverty require input from stakeholders, as well as sociological and marketing research that explores use patterns, fuel type and availability, and user preference. Also important is the development of quantitative, significant, and reproducible performance metrics and test protocols that lead to the development of cook stove pollution and efficiency standards. Creation of successful business models that result in the marketing, distribution, and sales of 250,000,000 improved stoves each year to customers that live far from conventional transportation arteries, with incomes of less than \$2.50 US/day, may provide an even greater challenge [25]. Also, potential unintended consequences, such as the increased use of stoves solely to generate electricity at extremely low efficiency (*i.e.*, not exploiting “waste heat” but burning biomass at a rate of $5 \text{ kW}_{\text{Thermal}}$ to generate a mere 5 W_{el}), will need to be considered.

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